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VISCOSITY OF METALS IN EXPLOSION WELDING

I. D. Zakharenko, et al

Foreign Technology Division
Wright-Patterson Air Force Base, Ohio

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by

I. D. Zakharenko and V. I. Mali

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

GREEK ALPHABET

Alpha	Α	α	α		Nu	Ν	ν	
Beta	Β	β			Xi	Ξ	ξ	
Gamma	Γ	γ			Omicron	Ο	ο	
Delta	Δ	δ			Pi	Π	π	
Epsilon	Ε	ε	ϵ		Rho	Ρ	ρ	ϱ
Zeta	Ζ	ζ			Sigma	Σ	σ	ς
Eta	Η	η			Tau	Τ	τ	
Theta	Θ	θ	ϑ		Upsilon	Υ	υ	
Iota	Ι	ι			Phi	Φ	φ	ϕ
Kappa	Κ	ϰ	κ	ϰ	Chi	Χ	χ	
Lambda	Λ	λ			Psi	Ψ	ψ	
Mu	Μ	μ			Omega	Ω	ω	

VISCOSITY OF METALS IN EXPLOSION WELDING

I. D. Zakharenko and V. I. Mali
Novosibirsk

In the glancing collision of metal plates moving at high rates two different phenomena may occur. At large contact angles a cumulative stream is formed [1]. At a smaller contact angle the stream disappears, the interface has a wavy shape [2], and welding of the plates occurs.

To describe the flow without the cumulative stream we shall, as in [3], make the following assumptions.

1. The metal of the plates prior to contact and in the same region after contact, where shear forces are not present, is considered an ideal fluid.

2. Metals flowing together after contact, i.e., behind the point of contact, are considered a viscous fluid.

The excess in the horizontal pulse component at the point of contact in the case of cumulation is compensated by the reverse stream. In the wave regime the excess in the horizontal component is compensated by the "submerged stream." Its velocity is less than

that of the contact point, and the stream is dissipated by the effect of viscous forces. By measuring residual shifts in particles we can determine the viscosity coefficient of a given metal.

Figure 1 shows the experimental scheme. The upper plate 3 was accelerated by explosion products from the detonation of explosive 5 and collided with plate 1. The impact regime was selected such that welding of the plates occurred.

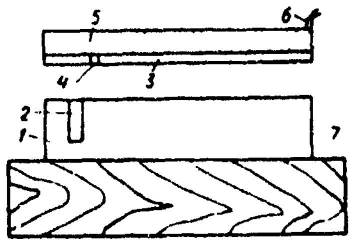

Figure 1. Scheme of experiments: 1 - lower plates, 2 - pressed plate, 3 - upper plate, 4 - pressed wire, 5 - explosive charge, 6 - detonator, 7 - wooden block.

After welding the specimens were cut in the direction of motion of the contact point and macrographs were prepared. In the photographs of the sections the horizontal displacement of fixed lines was measured. The characteristic graph representing the experimental dependence of the shift (z) as a function of distance to the interface in the welded plates (g) is shown as a solid line in Fig. 2.

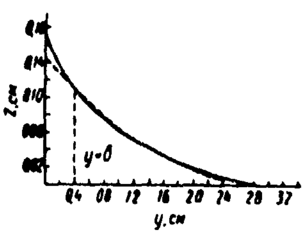

Figure 2. Shift in fixed line in lower plate: solid line - experiment; dashed line - parabola $z=a(y-\delta_2)^2$.

Processing the experimental curves $z=z(y)$ for the lower, thicker plate showed that $y>\delta_1$ (δ_1 is the thickness of the upper plate) this curve is well described by the equation of the parabola

$$z=a(y-\delta_2)^2 \qquad (1)$$

(δ_2 - the thickness of the lower plate), shown in Fig. 2 by a dashed curve.

Let us examine the impact of two metal plates at subsonic velocity in a system of coordinates connected to the contact point (O in Fig. 3). The parameters of the colliding

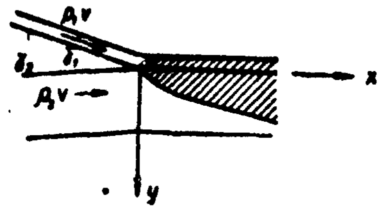

Figure 3. Movement of viscosity stream.

plates are such that the cumulative stream is absent.

If we examine the motion of the plates as the impact of streams of an ideal fluid at constant pressure, then the velocity along the free surface is constant. However, here the law of conservation of momentum along axis x will not be fulfilled: to the right of point O the pulse is greater than to the left.

We shall assume that the source of impulse is present at the contact point, and at this forms a unique submerged flow of a viscous fluid moving at a higher rate than the rate of contact (U). As we move to the right away from the contact point the submerged stream expands, covering an ever larger region of the flow (hatched region in Fig. 3). Because of the viscosity at infinity the flow rates with respect to plate thickness are never equalized.

In the unhatched region of the flow in Fig. 3, where velocity gradients are still absent and viscous forces are not active, a model of an ideal fluid can be used. The coordinate system shown in Fig. 3 was selected such that there is no vertical velocity component to the left of point O. From the law of preservation of momentum along axis x for colliding plates we find impulse (I) accumulated at point O

$$I = \rho_1 \delta_1 U^2 (1 - \cos\gamma_1) + \rho_2 \delta_2 U^2 (1 - \cos\gamma_2),$$

where ρ is the density of the material.

If we know the accumulated impulse, then it is easy to determine the velocity of the plates at infinity (u^{∞}), the expression for which in the case of plates with the same density, colliding at small angles, has the form of

$$u_{\infty} = U \frac{2\delta_1 \delta_2}{(\delta_1 + \delta_2)^2} \sin^2 \frac{\gamma}{2}.$$

Let us study the diffusion of the horizontal velocity to the right of the contact point, which occurs as a result of viscosity. We will study the case of impact between metals of the same density and viscosity. We have the generalized Stokes equation for steady-state motion of an incompressible viscous fluid

$$U\cdot\frac{\partial u}{\partial x}=\frac{\partial}{\partial y}\nu\cdot\frac{\partial u}{\partial y},$$

where μ/ρ is the kinematic viscosity coefficient.

Now let us integrate this equation from $x=-\infty$ to $x=\infty$ everywhere except the line which passes through the contact point:

$$U\int_{-\infty}^{\infty}\frac{\partial u}{\partial x}dx=\frac{\partial}{\partial y}\nu\cdot\frac{\partial}{\partial y}\int_{-\infty}^{\infty}u\,dx,$$

or

$$U[u_{\infty}-u_{-\infty}]=U\nu\cdot\frac{d^2z}{dy^2}.$$

Here $\int_{-\infty}^{\infty}u(x,y)dx=Uz(y)$, where $z(y)$ is the shift in the point from its original position. Since u_{∞} represents an addition to the velocity of the contact point to its left, which is equal to zero, we get

$$\nu\cdot\frac{d^2z}{dy^2}=u_{\infty}.$$

Then

$$z(y)=\frac{1}{2\nu}u_{\infty}y^2+Ay+B,$$

and constants A and B are determined from the following boundary conditions

$$\frac{\partial z}{\partial y}=0,\ z=0 \text{ when } y=\delta_2.$$

Finally, we get the shift in the lower plate

$$z(y)=\frac{U}{\nu}\frac{\delta_1\delta_2(y-\delta_2)^2}{(\delta_1+\delta_2)^2}\sin^2\frac{I}{2}. \qquad (2)$$

If we use the representation of (1) for $z(y)$, which is correct for $y>\delta_1$, then from (2) we get

$$\nu=\frac{U\delta_1\delta_2}{u(\delta_1+\delta_2)^2}\sin^2\frac{I}{2}. \qquad (3)$$

The velocity of the contact point was measured in preliminary experiments by means of streak photography. Angle γ was calculated from the formulas given in [2]. The results of processing certain experimental data according to formula

$$\mu = \frac{\rho U \delta_1 \delta_2}{(\delta_1 + \delta_2)^2} \sin^2 \frac{\gamma}{2}$$

are given in the table.

Material	δ_1, cm	δ_2, cm	$U \cdot 10^{-5}$ cm/s	γ	$\mu \cdot 10^{-5}$ P	
					$y=\delta_1$	$y=2\delta_1$
Aluminum (D16)	0,2	2	2,5	20°30′	0,65	0,66
	0,4	3	3,1	14°	0,74	0,79
Copper (M3)	0,4	1,4	1,7	21°	2,1	2,7
	0,4	2,4	4,2	14°20′	2,5	2,0
Steel (St3)	0,4	2,8	3,1	15°20′	3,9	4,1
	0,4	3,0	4	14°20′	4,8	4,8
Niobium	0,2	2,9	2,5	18°	2,2	2,2
	0,2	2,85	2,1	13°10′	2,1	2,2
Titanium	0,4	3,55	2,5	22°32′	4,3	4,3
	0,4	3,55	2,7	21°	4,2	4,4
Lead	0,23	2,3	1,2	10°	0,56	0,52
	0,21	2,7	1,4	9°30′	0,55	0,53

From the data of the table it follows that the numerical values of the viscosity coefficient for steel coincide with the results of studies by A. A. Il'yushin [3] and S. M. Popov [4]; the viscosity coefficients for aluminum coincide with the results of studies by A. D. Sakharov, and others [5], V. N. Mineyev, and Ye. V. Savinov [6].

The viscosity values for copper and steel do not agree with the data of [5]. One should, however, be wary of the results of [5], since in the experiments a constant flow behind the front was not obtained. In the opinion of the authors of [5] sufficiently great values for the length and diameter of the explosive charge

and also for the diameter of the profile disk should assure a constant flow behind the shock wave front, although in using recesses with ka_0=1.74, for example, the aperture angle of the latter was 2γ=120°. In this case the stream which we observed is formed at the vertex of the recess. Thus, in the experiments of [5] after a shock wave of sinusoidal profile emerges into a wedge disturbances from the cumulative streams arrive on its surface. These disturbances, already moving through the compressed metal, have a higher velocity than the front of the first sinusoidal wave, and thus overtake it at a certain distance. In this case there is also a phase shift in the sinusoidal disturbance, which was also observed in [5].

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